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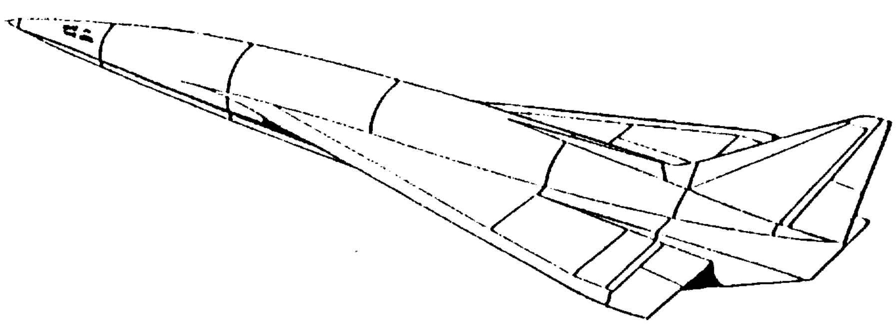

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INTRODUCTION

Over the past thirty years application of hypersonic technology in the United States has focused on rocket-powered, space re-entry systems. These systems include ballistic-missile warheads, reconnaissance-satellite capsules, and manned spacecraft, such as Mercury, Gemini, Apollo and Space Shuttle. Early systems were nonreusable, but Space Shuttle development moved into the realm of reusable equipment. These systems experience hypersonic flight in the atmosphere for only a short time--no more than a half-hour. Vehicles capable of missions involving several hours of hypersonic flight, however, are nonexistent. See reference 1.

This report addresses a conceptual transatmospheric aerospacecraft designed for two missions requiring hypersonic flight of several hours duration. The aerospacecraft would takeoff and land horizontally from a conventional airport runway. It would be capable of (1) achieving orbit from takeoff in a single stage (single stage to orbit, SSTO) and performing like a spacecraft or of (2) performing like an aircraft and cruising hypersonically within the atmosphere to its destination. It would be manned and reusable. The primary objective of this aerospacecraft is low-cost, reliable, rapid turn-around, access to space. See reference 2.

Despite relatively modest levels of support, research and development has generated progress in hypersonic technology which is applicable to such an aerospacecraft. Hypersonic aerodynamics has advanced well, and, with application of recent developments in computational fluid dynamics, probably can supply a solid foundation for the aerodynamic design for future hypersonic aerospacecraft. Areas where further research is needed in aerodynamics include boundary layer transition, interference heating, and control effectiveness. Promising new concepts for scramjet propulsion systems and lightweight long-life structures are being developed. Advanced materials are being explored which retain strength and stiffness at high temperatures. Propulsion, structures, and materials technologies, however, are less well developed than aerodynamics, and a great deal more work must be done to bring them up to a level which can support design, development, and construction of a transatmospheric aerospacecraft. See reference 3.

Design of structures for a transatmospheric aerospacecraft is a very demanding task. The dominant consideration when compared with subsonic and supersonic aircraft structural design is the major importance of aerodynamic heating. Heating effects are exhibited in two aspects. First, the total thermal load causes the structure to heat up and typically degrades the properties of materials used to fabricate the structure. Second, temperature gradients introduce thermal stress into structural elements, which turn out to be as important as or predominant over stresses due to other loads on the structure, such as air loads, thrust loads, and landing loads. Lightweight structure is of crucial importance in the transatmospheric aerospacecraft, especially for the SSTO mission, because relatively small changes in aerospacecraft weight can control whether or not orbit is achieved.

The purpose of this report is to discuss major considerations in structural design of a transatmospheric aerospacecraft, to indicate the general direction of progress in structures and materials technology, and to identify technical areas in structures and materials where further research and development is necessary. Typical missions are described, and major loads in each phase of the mission are identified. Various structural concepts under study, and materials which appear to be most applicable are discussed. Structural design criteria are discussed with particular attention to the factor-of-safety approach and the probabilistic approach. The report closes with a discussion of structural certification requirements for the aerospacecraft. The kinds of analyses and tests which would be required to certify the structural integrity, safety, and durability of the aerospacecraft are discussed, and the type of test facility needed to perform structural certification tests is identified.

TRANSATMOSPHERIC AEROSPACECRAFT CHARACTERISTICS

The transatmospheric aerospacecraft (figure 1) would take-off and land horizontally and operate from conventional runways. It would be capable of hypersonic cruise in the upper atmosphere and capable of flying to orbit in one stage. The two mission profiles are illustrated in figure 2. In one profile the vehicle would take off and climb to a high altitude and then accelerate hypersonically. At the appropriate speed and altitude a relatively small rocket engine would cut on and boost the vehicle into orbit. It would become a spacecraft in orbit around the earth and subsequently reenter the atmosphere, and land in a conventional manner. In the other profile, the vehicle would take-off, climb to a high altitude, and cruise through the atmosphere at hypersonic speeds to its destination and land conventionally. The vehicle would be manned and capable of carrying passengers and/or cargo. It would be capable of repetitive missions with minimum turn-around time and ground support infrastructure.

Candidate engines for the propulsion system for this vehicle are rockets, airbreathing turbojets, and airbreathing ramjets and scramjets (supersonic combustion ramjets). Most likely a combination of these engines would be required. Because of the extremely high energies involved, it is very likely that the primary fuel for liquid rocket engines and ramjet and scramjet engines would have to be hydrogen with its exceptionally high specific impulse. Turbojet engines could be used for takeoff and acceleration to speeds high enough for ramjet and scramjet engines to start. For hypersonic acceleration and cruise the airbreathing ramjet and scramjet engines would be required because of substantially better propulsive efficiency than either rockets or turbojets at hypersonic speeds. Rocket engines would probably be required for a final boost into orbit.

The airbreathing propulsion system operates efficiently at high dynamic pressure. Because of the duration of time the vehicle is operating at high dynamic pressures, severe heating effects must be withstood. This situation leads to requirements for major increases in structural weight to combat potentially catastrophic deterioration in structural integrity. The vehicle structural design, therefore, involves a very fundamental tradeoff between structural and propulsion considerations. The design flight trajectory can have a major influence on the selection of airframe structural arrangement, structural concepts and materials, insulation approaches, and cooling techniques.

The wings of the aerospacecraft would be sized to meet take-off and landing requirements and handle maneuver and control functions. The fuselage would be sized to encompass fuel tankage, crew cabin, payload bay, and passenger cabin. To reduce drag, engine modules must be tightly integrated into the fuselage body which is used as a compression wedge for the engine inlet and a thrust wedge for the engine nozzle.

STRUCTURAL DESIGN ENVIRONMENT

Major loads on the transatmospheric aerospacecraft in various phases of the flight-path are identified in the table in figure 2. Takeoff and landing conditions are characterized and compared with other categories of vehicles in figure 3. Flight envelopes for the transatmospheric aerospacecraft are compared in figure 4 to the Space Shuttle and current supersonic aircraft in terms of altitude as a function of flight Mach number. The aerospacecraft experiences major heat loads in the ascent and the hypersonic acceleration and cruise phases of flight whereas the Shuttle experiences the major heat loads upon reentry. The thermal environments for various manned hypersonic vehicles are broadly compared in figure 5.

Typical generic structural design environments are shown in figure 6 for various portions of the vehicle with an airbreathing scramjet engine. The chart in figure 6 pertains, on the left, to the airframe and, on the right, to the engine. It displays peak heating rates for ascent and descent flight, maximum aerodynamic pressures, maximum acoustic pressures, maximum inplane structural loads, cycle life, and design operational life. Data is presented for the following surfaces: forward fuselage, inlet ramp, inlet cowl, wings, tails, engine diffuser, combuster, exit cowl, and nozzle.

The most severe heating rates are localized at the inlet cowl lip, vehicle nose, and wing leading edges. Typical values at these locations are shown in figure 7. A unique aerothermal phenomenon can occur at the inlet cowl lip illustrated in figure 8. The heating rate of 3500 Btu/sq. ft.-sec. given in figure 7 represents the value behind a bow shock of a typical cowl lip configuration. However, the aerospacecraft is configured overall in such a way that the oblique shock from the vehicle nose impinges on the cowl lip during hypersonic acceleration or cruise. This arrangement ensures that all compressed air is captured by the engine. But this oblique shock (identified as an incident shock in fig. 8) interacts with the bow shock at the cowl lip and generates a supersonic jet in the subsonic flow behind the bow shock. This jet impinges nearly normal to the cowl lip surface and causes a very localized hot line with heating rates from 6 to 30 times the stagnation heating in the absence of the incident shock impingement. See references 4 and 5 for more detailed discussion of the phenomenon. This situation must be addressed with special attention to develop acceptable design solutions.

STRUCTURAL CONCEPTS

Structural concepts that merit consideration as candidates for application to a transatmospheric aerospacecraft are discussed (see refs. 6 and 7). Concepts which employ ablative heat shield materials such as used on Apollo, Gemini and Mercury space capsules are not considered in this report. Ablators are attractive only for short exposure to the very high temperatures involved and, unless easily refurbishable, are not suitable for reusable vehicles capable of single-stage-to-orbit and hypersonic cruise.

General Applications

Hot Structure. In this concept the moldline structure serves as the primary load-bearing structure. The external surface of the structure is permitted to attain a radiation equilibrium temperature dependent upon the aerodynamic heating environment and material limitations. Hot structure is typically employed in supersonic aircraft; for example, this type of structure is used on the YF-12 and was used on the X-15 aircraft. Advantages of hot structures are that they are conventional and relatively simple. They are potentially very durable, and many structural configurations are possible (see fig. 9). They can be designed to be easily inspected and maintained. On the other hand, hot structures are likely to be heavy, the outer surfaces must be relatively smooth, and they must withstand high thermal stresses.

Metallic Heat-Shielded Structure. This concept employs a moldline heat shield and insulation to protect the primary structure from aerodynamic heating (see figure 10). Advantages of heat-shielded structures are that a wide range of conditions can be met by varying the heat shield materials and the insulation materials which back up the shield. With careful attention to detail, reasonable inspectability and maintainability can be attained. The concept is durable and reusable. The disadvantages are that the designs must restrict boundary air leakage and also provide for thermal expansion. Surface roughness can be present to degrade aerodynamic performance if adjacent shields overlap, for example, Designs are rather complicated, and inadvertent heat shorts can occur to the primary structure.

Externally Insulated Structure. The primary structure is protected by bonding an insulation material on the external surface as shown in figure 11. This concept is exemplified by the reusable surface insulation on Space Shuttle Orbiter. Advantages are simplicity, and ability to learn from Shuttle operational experience. Disadvantages are that the surface insulation has rather limited reusability, and inspection of the structure is hampered. Current reusable surface insulation materials are not very durable, and mission turnaround time may be increased if insulation must be replaced.

Actively Cooled Structure. The aerospacecraft will have large volumes of cryogenic fuel aboard. It is natural to use this fuel as a heat sink to cool parts of structure which experience high heating. Structural concepts which are actively-cooled by flowing liquid fuel through passages adjacent to the structure are illustrated in figure 12. A plumbing system is employed to circulate the fuel/coolant which is subsequently delivered to the propulsion system. A major concern with this approach involves matching airframe heat loads with available fuel heat sink; and thermal protection in the form of insulation and/or heat shields may be required to be coupled with active cooling systems. The advantage to the active-cooling approach is that the structure potentially is light weight. Disadvantages are the complication and weight of a plumbing system to circulate the coolant, concern for reliability of the plumbing, and difficulties in fabricating the structure with the intricate passages required to supply adequate cooling to all parts of the structure.

Vehicle Nose and Leading Edges

The aerospacecraft nose and wing leading edges experience higher localized heating than other locations (fig. 7). Specialized structural approaches may be required in these local zones.

Hot Structure. Conventional nose and leading edge designs are desirable for reasons of simplicity and past experience. Higher temperatures, however, drive the designs to use of heavy materials such as refractory metals and ceramics. This situation leads to large weight penalties for the hot structure approach. Lighter carbon-carbon composites have potential use as hot structure for nose, leading edge, and control surface designs. A significant technical problem with this material is the need for effective oxidation protection.

Externally Insulated Structure. Use of external insulation to protect vehicle nose and leading edge structure is one simple approach. The drawback to this approach is the difficulty in finding materials which are sufficiently durable and reusable in the high temperature environment.

Active Cooled Structure. Nose and leading edge structures are candidates for cooling by use of a flowing fluid as illustrated in figure 13. This concept is compatible with an overall actively cooled airframe design. The coolant can be collected and moved through passages in panels adjacent to the leading edges and subsequently routed to a heat exchanger or rejected by radiation.

Phase-Change Material Cooled Structure. Heat pipes can be used to distribute heat evenly over the leading edge and nose regions (see fig. 14). This approach eliminates hot spots along the flow stagnation line. The particular concept shown in figure 14 involves use of high specific strength carbon-carbon to accomodate thermal/structural loads and very thin refractory metal D-shaped heat pipes embedded within the carbon-carbon structure to transport stagnation heat aft where it can be rejected by radiation. The heat pipes are sized and spaced close enough so that, in the event of failure, the ablation protection afforded by the carbon-carbon is sufficient to enable safe reentry. Further details are contained in reference 8.

Cryogenic Tankage

A large portion of the fuselage of an aerospacecraft is composed of cryogenic tankage which increases thermal gradients in the vehicle structure. These gradients complicate the structural design by presenting the potential of large thermal stresses. In addition, structural design of these tanks must address the containment of liquid hydrogen and oxygen as well as thermal protection and support of vehicle mechanical and thermal loads. The extremely low temperature of liquid hydrogen tanks causes other gases to condense. Without proper insulation or purging, air (or any gas except helium) cryopumps, that is, it condenses on the tank walls so rapidly a partial vacuum is formed. The vacuum draws additional air to the tank where it, in turn, condenses. Cryopumping transmits heat to the tank and causes hydrogen boiloff and also causes a safety hazard because the initial liquefaction of air is oxygen rich (ref. 9). For vertical launch vehicles cryopumping is not as significant a problem as for the aerospacecraft because lightweight closed-cell foam insulations exist which can withstand the less severe vertical ascent environment. Such an insulation layer is used successfully on the exterior of the Space Shuttle external tank, for example.

Integral Versus Nonintegral Tankage. A significant overall design consideration is the choice between integral or nonintegral tankage. By integral tankage is meant the tank walls are also the primary structural paths for the airframe and carry body shears and bending moments as well as internal pressure and slosh, inertial, and gravity loads. Nonintegral tankage, on the other hand, means that the tanks are separated from airframe structure and do not carry body shears and bending moments. The nonintegral tankage has distinct operational and design advantages over the integral tankage. These advantages include the possibility of removing the tanks for inspection or maintenance and repair. Also, differential thermal expansion between the cryogenic tankage and the primary structure can be accommodated easily to reduce thermal stresses. Furthermore, nonintegral tankage can be configured in circular shapes (spherical, cylindrical, conical) somewhat independent of the external moldline of the vehicle and thereby carry pressure loads efficiently. In addition, the simple, well-defined stress distribution of circular-shaped nonintegral tanks aids in analysis for fracture mechanics and minimizes failure modes and points of potential failure. On the other hand, integral tank systems are likely to be simpler and lighter overall than the nonintegral systems. Mechanical and thermal loads are carried by the minimum number of structural elements, so there is less redundancy in the integral systems. The most satisfactory approach must take into account all aspects of the vehicle design, construction and operation.

Tank Insulation Concepts. Example tank structure and insulation are shown in figure 15 in which the distinction between integral and nonintegral tankage is illustrated. Insulation of flightweight cryogenic tankage is a technical area where a great deal of development work needs to be done. Low density foam insulations have been proposed for use on the inside or the outside of the tank wall. When used on the inside of the tank wall, foam insulation requires an effective vapor barrier to prevent hydrogen gas permeation of the foam. Permeation of hydrogen gas into these insulations increases their thermal conductivity and reduces insulation effectiveness. Foam insulation applied to the exterior of the tank may require protection from aerodynamic shear forces to maintain its integrity. In addition, air can permeate external insulation, increase the thermal conductivity, and actually condense at the tank wall to cause fuel boiloff. Thus, a vapor barrier is important for external insulation as well as for internal insulation.

Another approach to cryogenic tank insulation involves use of evacuated metallic panels. Multilayer paneling concepts have been proposed which are fabricated in such a way as to provide interior openings which can be evacuated. Honeycomb sandwich panels can also be evacuated to meet this need. This design approach is potentially very effective. Large-scale structures of this type, however, have proved to be unreliable because of difficulties in making them leak-proof. Insulating capability deteriorates greatly if leaks are present.

MATERIALS

A broad spectrum of materials are candidates to meet structural requirements for an aerospacecraft. Because of stringent limitations on structural weight, low density, thin gage alloys and composites are required. Specific strength and specific density of various classes of candidate materials are shown in figure 16. Concise summaries of research on materials for hypersonic aircraft are contained in references 7 and 10.

Metals

Aluminum alloys. Although conventional 2000 and 7000 series aluminum alloys are useful to moderately elevated temperatures (350F) only, it is expected that they will continue to make up a portion of the structure for hypersonic airframes. They may be used in substructure and for tankage including cryogenic tankage. Development of aluminum-lithium based alloys and high temperature aluminum alloys could improve performance of hypersonic vehicles (see ref. 7). Current research on aluminum-lithium alloys is addressing low fracture toughness, fatigue crack growth, environmental stability and microstructure. Recent progress has been made in the development of a new Al-Li alloy (called Weldalite™) which is weldable, has excellent strength and good fracture toughness, and does not require cold work to achieve maximum strength. The significance of this latter feature is that parts fabrication may be possible using superplastic forming with heat-treatment subsequent to forming.

Several new aluminum alloy compositions have been developed which retain their mechanical properties to temperatures as high as 550F. These alloys could be attractive for hypersonic airframes because requirements for thermal protection would be reduced.

Beryllium alloys. Beryllium is a widely used metal with some very attractive properties. It can be used up to about 1000F. It has low density and high modulus of elasticity--making it attractive for application to stiffness-designed structural components. It also has high thermal conductivity and so has applications where good transfer of heat is required. Disadvantages of beryllium are poor toughness properties and toxicity of the oxide. Despite these problems beryllium is used in a variety of applications especially in spacecraft. It can be handled and machined with modest precautions, and there is considerable experience with its fabrication and application. Research on beryllium alloys is focusing on rapid solidification rate (RSR) processing to improve the stability of the microstructure and raise the temperature capability. See reference 10.

Titanium alloys. Titanium alloys have been used extensively in applications typically up to 1000F. Alloys that are weldable and have good corrosion resistance have been developed for application to aircraft turbine engines, and they should find application in hypersonic airframes. Recently, emphasis has been directed to RSR processing which promises to extend the temperature at which titanium is useful to above 1500F. In RSR processing, molten metal is atomized then cooled very rapidly. The resulting powder is consolidated to fabricate a part. This method allows the formation of compositions and microstructure features not attainable by conventional processing. RSR gives better stabilization of the microstructure, for example, which not only improves the elevated temperature properties but also extends the period of exposure time for retention of improved properties (refs. 7, 9 and 10).

Titanium-aluminide intermetallic compounds (Ti_3Al and TiAl) are also attractive for elevated temperature applications. Efforts are directed to improving properties and use temperatures by controlling microstructure through alloy chemistry and processing techniques such as RSR . Studies have been made in powder-making process development and subsequent consolidation techniques. Fabrication to thin gage sheet as well as forming, and joining technology are under development. Major hurdles that must be overcome include environmental effects, embrittlement from hydrogen exposure, permeability, and catalytic effects. Recent work on oxidation and catalysis is reported in reference 11. Limited room-temperature ductility, characteristic of titanium aluminide, is also being addressed (ref. 9).

Superalloys. So-called superalloys are nickel, iron, or cobalt-based alloys which are used effectively up to 2000F. They are used extensively in aircraft turbine engine applications. In general, superalloys have excellent oxidation resistance and good microstructural stability. Superalloys in sheet, plate and forgings have been well characterized and have been widely used in the aerospace industry. The X-15 was made of Inconel-X, and Inconel 718 provides the best combination of strength and fabricability (see ref 6). The cobalt-based alloy, L605, provides excellent properties in the cold worked condition; however, its use is limited to section sizes that can be cold worked. Also, in cold worked sections requiring welding, the properties are reduced locally by the heat of welding (see ref. 6). Other superalloys which might have application in hypersonic airframes are Rene' 41, Haynes 188, Inconel 617, and MA-956.

Refractory alloys. Refractory alloys used in the aerospace industry are primarily columbium and tantalum alloys. Columbium alloys have a maximum use temperature of 2400F, and tantalum alloys have a maximum use temperature of 2800F. Columbium alloys have about half the density of tantalum alloys. Of the columbium alloys, F-85 provides the best combination of strength, high temperature capability, and fabricability. Of the tantalum alloys, T-222 provides the best overall combination of properties. See reference 6.

Ceramics. An outstanding feature of ceramics is their environmental resistance without dependence on coatings. They may find application in monolithic form as airframe nose and leading edge inserts.

Composites

Resin matrix composites. Graphite-epoxy composites are the most highly developed at the present time. These materials are limited in application to temperatures less than 250F. Application to hypersonic aerospacecraft will certainly be limited to internal structure.

The application temperature range for resin matrix composites can be extended by use of matrix materials other than epoxies. The polyimides are projected for use at about 500F while graphite-polybenzimidazole and graphite-polyimidazoquinazoline may be useful up to 900F. These materials require special processing, and fabrication techniques need improvement.

Metal matrix composites. Boron-aluminum and Borsic-aluminum are the most mature metal matrix composite systems. These materials have a significant data bank of material properties. Manufacturing techniques for making the basic material and structural components have been developed. Large, complex structures have been designed, fabricated and tested.

Boron-aluminum may be useful up to 600F. Large complex structural components have been tested successfully at this temperature. Titanium interleaving may increase the useful temperature range to 800F or higher. Boron-aluminum can be interleaved with titanium either by diffusion bonding, roll-bonding or by low temperature liquid phase bonding. Such structures have been fabricated and tested successfully at 600F.

The high cost of boron and Borsic filaments has led to increased effort on graphite-aluminum composite. This system, however, is not as developed as boron-aluminum, and the potential of the mechanical properties offered by the graphite-aluminum combination, based on the rule of mixtures, has not yet been realized. Also, there has been no significant success in developing the techniques that will be needed to fabricate major structural components from this material.

Titanium matrix composites are superior to boron-aluminum from the standpoint of shear strength, temperature capability, and erosion resistance. The titanium matrix technology, however, is not as advanced as boron-aluminum. Various titanium alloys have been evaluated as matrix materials in combination with boron, Borsic or silicon carbide fibers. In general, Borsic fiber yields higher strength than the uncoated boron. Silicon carbide fibers are not as strong as boron or Borsic at room temperature, but silicon carbide becomes competitive with the other two at about 1000F. The elevated temperature behavior and lower cost of silicon carbide makes it an attractive candidate fiber for hypersonic applications.

Titanium-aluminides are also potential matrix materials for composites. These composites have potential for use in the range from 1500F to 1800F. Research is directed toward development of silicon carbide fibers and possibly titanium diboride fibers for use with titanium aluminide matrices. Efforts are focused on fabrication techniques by foil rolling, plasma spraying, arc spraying, and powder metallurgy processes. In one process, for example, silicon carbide fibers are sandwiched between layers of titanium aluminide foil and consolidated by hot isostatic pressing (ref. 12).

Graphite-copper composites are under development for use as radiator panels for space stations, and tungsten-copper composites are being studied for use in the combustion liner for the Space Shuttle main engine. These metal-matrix composites have high thermal conductivity, and may find application in the engine cowl lip of an aerospacecraft where this property is essential. See reference 12.

Composites using superalloys as matrix materials are the least developed metal matrix systems. The principal concern has been degradation of properties resulting from fiber/matrix interaction during extended exposure to elevated temperatures. Methods for fabricating structural components have not been developed.

Exothermic dispersion composites. An exothermic dispersion process developed by the Martin Marietta Research Laboratories produces a material that contains a fine, close-spaced uniform distribution of second phase particles which are formed and grown in situ as distinct from being mechanically mixed as a separate additive. As a result, the particle/matrix interfaces are clean and well-bonded and develop highly effective reinforcement.

The process, identified by the symbol XD, has been applied both to titanium and aluminum. The dispersoids, typically titanium diboride, can be tailored to some extent to produce a variety of second phase distributions where the particles can have controlled shapes ranging from spherical to long needles. In many cases the dispersoids once formed, are very stable and can survive a remelting process, so the material subsequently can be cast into shaped elements without destroying the reinforcement.

Microstructures which result from the XD process are attractive because they lead to improved strength and use-temperature capabilities. XD composites will be useful as high temperature structural materials either as sheet or as shaped elements, but they also may be suitable matrix materials for continuous-filament reinforced composites. The titanium-based XD composites have progressed more rapidly than the aluminum-based work, and the titanium process has been scaled up to a 250 lb ingot size. See reference 10.

Carbon matrix composites. Carbon-carbon composites are used in many applications including reentry vehicles and rocket motor nozzles. These materials are well characterized, and there is a large knowledge base available regarding their fabrication and use. Several companies specialize in the fabrication of carbon-carbon components, and there are various basic methods for making structural shapes. Carbon-carbon has superior structural properties compared to other materials at 3000F and above. Because of excellent high temperature properties these composites should find application in hypersonic vehicle nose caps and leading edges.

While carbon-carbon composites have the potential for use as load-bearing, thin-gage structural components in hypersonic aircraft, there is a major technical problem involving protection against oxidation above 900F. Protection coatings have been devised which work reasonably well in situations where the material is taken up to a single high temperature and then cooled, but they face significant problems when subjected to temperature cycling. The basic difficulty is that existing protection coatings use refractory materials such as silicon carbide. These materials work well from a chemical standpoint, but they crack due to thermal expansion mismatch between the silicon carbide and the carbon-carbon substrate. To alleviate this problem, additional interlayers are used which oxidize to form a glass that can flow and seal cracks. Unfortunately, these glasses do not flow readily at intermediate temperatures, reducing their effectiveness in the 1000F-1500F temperature range. Recently, improvements have been made in oxidation protection schemes, and experiments have shown that cyclic temperature loading can be withstood successfully on small specimens. See reference 10.

Ceramic matrix composites. Over the past 10 years notable advancements have been made in ceramic matrix composites. They offer the advantages of high temperature strength, high strength-to-weight, and outstanding environmental resistance without dependence on coatings. Ceramic matrix composites could find applications in airframe, control surfaces, and engine structure. A limitation for these materials is that no fiber is known for use above about 1800F for long exposure times. Development of a stable, small diameter fiber for such applications needs to be addressed. These materials exhibit resistance to hot hydrogen, and this attribute has stimulated widespread research and development which promises near term improvements (ref. 10).

Coatings

Many materials and structural components on a hypersonic aerospacecraft will require coatings for temperature control or for environmental protection. For temperature control, coatings can be designed to have high emissivity and to be noncatalytic to the recombination of the dissociated gases present in the hypersonic airflow adjacent to the vehicle. This action can lead to reductions in surface temperatures of several hundred degrees.

For environmental protection, two significant conditions pertain to the aerospacecraft. First, much of the airframe and engine structure is exposed to a hot oxidizing atmosphere, and coatings are required for oxidation resistance. Titanium aluminides and carbon-carbon, for example, require oxidation protection (ref. 11). Second, the use of hydrogen for cooling structure is a particularly unique situation for the aerospacecraft. This technique exposes extensive areas of structure to hydrogen, which readily diffuses through most materials and can form brittle compounds within the materials. Hydrogen barrier coating development is a critical challenge because the coating must be thin, lightweight, resistant to damage, and applicable to complicated shapes including intricate internal cooling passages. See reference 10.

STRUCTURAL DESIGN CRITERIA

The Factor of Safety

In simplest terms the fundamental process in strength design of an aerospace vehicle structure involves determination of the maximum load that the structure is expected to experience in its lifetime and determination of the expected strength of the structure. The problem is to assure that during its useful lifetime the strength of the structure is equal to or greater than the maximum load it will experience. The maximum load that the structure is expected to experience in its lifetime is identified as the limit load. It is recognized that there are uncertainties in this limit load and uncertainties in the determination of the strength of the structure. To accomodate these uncertainties a quantity is specified which is called the factor of safety. This quantity is multiplied by the limit load to obtain a higher load which is called the ultimate load. The structure is then designed to carry ultimate load to assure structural integrity under all operating conditions with a high level of confidence.

Many factors of safety are used in practical design of aerospace vehicles. Typical factor-of-safety values follow:

Missiles	1.25
Manned Spacecraft	1.40
Manned Aircraft	1.50
Pressure Vessels	2.00

In addition, there are special factors of safety specified for design of joints, windows, doors, hatches, and hydraulic actuators and lines, for example. How do we know that these factor-of-safety values are correct? Only by experience. Over a period of years values such as these have evolved, and experience has shown that they are good and account for uncertainties in design reasonably well.

In addition to adequate strength, the airframe structure must possess adequate stiffness to withstand flutter and divergence, have acceptable tolerance to damage, and have acceptable fatigue life. The following documents contain detailed structural design criteria and standards applicable to various classes of aircraft:

1. MIL-A-8860 (USAF) Series-Aircraft Strength and Rigidity

2. MIL-A-8870 (USAF) Aircraft Strength and Rigidity--Flutter and Divergence

3. MIL-A-87221 General Specifications for Aircraft Structures

4. MIL-A-83444 (USAF) Military Specification--Airplane Damage Tolerance Requirements

5. MIL-STD-1530A Military Standard--Aircraft Structural Integrity Program

6. Federal Aviation Regulations, Part 23

7. Federal Aviation Regulations, Part 25

Probabilistic Design

But what if the structure under design involves structural configurations, materials, loading conditions, operating environment and other features for which there is no body of experience? Then how good are these factors of safety? We don't know!

If structural integrity can be thought of in terms of acceptable risk, then there are techniques for determining what the factor of safety should be. That is, if an acceptable risk can be specified for structural failure, then the factor of safety required to meet this risk can be established. The techniques involve a probabilistic approach to the design process as presented in reference 13.

Methods of probability are the tools which can quantify the effects of uncertainties in the loading and operating environment and uncertainties in the structural response and strength. When these quantities are known, then the risk of failure can be quantified, and some assessment can be made as to the acceptability of this risk.

Advantages to the probabilistic approach to design include:

1. An assessment of the risk involved in the structural design can be made.

2. Increased realism in factors of safety can be established.

3. The importance of individual uncertainties can be established.

4. A determination can be made as to which parts of the structure involve the most risk in design.

   (a) It may be possible to improve the uniformity of quality of the design.

   (b) Structural test program can be developed with realism--areas can be identified where more thorough testing is required.

5. The possibility for optimized or minimum weight structure is enhanced. That is, structural weight can be saved if risk assessment indicates reduced factors of safety are acceptable.

6. Risk in the structure can be compared with risks in other aspects of the overall design process.

7. The sensitivity of risk to various parameters can be determined and resources applied to the important parameters.

Disadvantages to the probabilistic approach to design include:

1. The approach is new and unconventional and is unfamiliar to structural designers. Gust loading, however, is typically handled in a probabilistic manner in conventional aircraft design.

2. The concept of "acceptable risk" is difficult to accept.

3. There is danger of design errors if safety factors are not uniform throughout the structure and design process.

4. The approach is more complicated than conventional design.

5. Uncertainties in the design process must be quantified, and such uncertainties are numerous and difficult to quantify.

6. Cost of structural analysis will be substantially increased.

7. Uncertainties in the design process may not be understood until it is too late to make design changes.

The most penetrating argument for considering the probabilistic approach in the design of a transatmospheric vehicle is that the domination of thermal effects in the design is unexplored territory. For example, how should thermal stresses in combination with mechanical stresses be treated in the design process? In the Space Shuttle project, design thermal stresses were increased by a factor of safety when thermal stresses were additive, but no factor was applied when thermal stresses were alleviating. But there is in the industry no concensus on this procedure or on the value of the factor of safety to use with thermal stress. In probabilistic design, it should be possible to treat thermal stresses and mechanical stresses on a consistent basis. In addition, the dominance of thermal effects in aerospacecraft design leads to the possibility that new and unfamiliar materials and structural concepts and unusual fabrication methods will be required for substantial portions of the structure. Conventional factor-of-safety values, therefore, do not have a historical basis for use with such components. Sensitivity studies can help determine where and when it is most beneficial to make the investment in determining the uncertainty ranges to be used in probabilistic design.

Because the factor of safety approach is so deeply entrenched in the design process and in the minds and experience of vehicle designers, it seems likely that adoption of the probabilistic approach in a thoroughgoing fashion will be slow and difficult. Perhaps an evolutionary process can be fostered in which the probabilistic approach is gradually introduced. A practical combination of the two approaches has been suggested by Roger Wilkinson, McDonnell Douglas Missile Systems Company, in which factors of safety are related to the probability of not exceeding the loading conditions. Specifically, Wilkinson suggests that the structure be divided into major components, such as nose, forward tank, center fuselage, aft fuselage, wing, tail, inlet ramp, engine supports, nozzle, and landing gear. Flight phases are then broken down into taxi, subsonic flight, transonic flight, hypersonic ascent, hypersonic descent, landing, and taxi, and uncertainty parameters are identified, such as, flight load variations, structural anomalies (materials and fabrication), and inaccuracies in loads analysis, strength analysis and thermal analysis. Subsequently, uncertainty analyses are conducted for each component, each flight phase, and each uncertainty parameter to generate probabilistic factors of safety. In this way, the factor of safety concept is not abandoned but rather is used in conjunction with probabilistic methods to conduct the design process. Two benefits ensue from this combined approach: (1) the designer is exposed to the probabilistic process within the framework of the familiar and comfortable factor-of-safety method, and (2) the factor-of-safety method can continue to be used for elements of the design process for which time and expense do not allow acquisition of the data required for probabilistic design.

CERTIFICATION

Structural certification is the process by which the vehicle designer and builder and the government assure themselves that the vehicle structure is strong enough and stiff enough to withstand the flight environment and capable of safe flight throughout its expected life. Typically, this process is composed of analysis, ground testing, and flight testing. Analysis is a major component of the process because only limited testing can be performed. A primary purpose of ground and flight testing must be to validate analysis methods which can then be used to certify for conditions not being tested. Static and cyclic ground tests are performed to assure that the structure will carry limit load or ultimate load in what is judged to be the most critical loading conditions and will have acceptable fatigue life. Flight tests are performed in a sequence of increasing speed and maneuvers with correlations to ground tests and analysis at each step of the program. Once limit speed and limit load factor maneuvers are demonstrated with proper correlations achieved, the vehicle is certified for full envelope flight.

To give an idea of the scope of a full-scale ground test program for structural certification, consider, for example, the only existing reusable hypersonic vehicle in the western world, the Space Shuttle Orbiter. The ground test program for the Orbiter included one complete full-scale structural test article and a number of full-scale components such as nose cap, wing leading edge, vertical stabilizer, and orbital maneuvering system pod. The complete test article was subjected to 39 static test conditions representing 32 critical design loading conditions, and the forward fuselage of this test article was subjected to combined thermal and mechanical loads. The component test articles were subjected to thermal and acoustic fatigue testing. Electrical radiant heaters and resistive blankets were used to accomplish the heating tests. See reference 14.

The ground test program for the only operational supersonic transport in the world, the Concorde, included two complete full-scale structural test articles (one static and one fatigue) and 14 full-scale components which together made-up almost another complete aircraft. Combined static mechanical and thermal loads were applied to one of the complete test articles and combined cyclic mechanical and thermal loads were applied to the other. Most components were exposed to various combinations of thermal, static and cyclic loads. Radiant heaters and blowers accomplished the heating. Fuselage pressurization testing was accomplished by filling the passenger cabin with polyurethane foam blocks to reduce risk of explosion and then pressurizing with air. See reference 15.

In 1988 a study was completed by five National Aero-Space Plane airframe contractors on test requirements for structural certification of hypersonic aircraft. Results are summarized in reference 16. The contractors agreed that structural certification is adequate when analyses, materials tests, ground tests of flight quality hardware, and flight tests demonstrate that the aircraft is flightworthy, safe, meets all applicable specifications, and can endure all life-time environments. The contractors felt that previous experience on existing vehicles, such as Shuttle and Concorde, has limited application to the type of aerospacecraft considered in this report. The transatmospheric aerospacecraft is manned, reusable, and consists mostly of hot structure, actively-cooled structure, and large cryogenic tankage. The structure must be very light-weight, tough and tolerant to the cryogenic hydrogen environment and large extremes in temperature. No existing flight vehicle encompasses all of these features.

A review of existing basic design criteria documents was made. It was concluded that the following documents are applicable in general to the aerospacecraft:

Documents 1-5 from STRUCTURAL DESIGN CRITERIA section (p. 17)

8. NASA SP-8507 Structural Design Criteria Applicable to a Space Shuttle

9. Tentative Airworthiness Standards for Supersonic Transport--Based on Federal Aviation Regulations, Part 25

These documents may need some modification through joint action by the government and contractors, but they constitute a good basis for initial criteria.

Test requirements for flight vehicle structural certification typically consist of coupon tests, small component tests, major component tests and complete vehicle tests. Material properties, environmental effects, and materials processing development data are acquired from coupon tests. Small component tests certify joints, attachments, structural panel, bulkhead, and frame design. Major component tests encompass body sections, wing and tail sections, and wing-body interface. Finally, the complete vehicle is normally subjected to static tests, durability or fatigue tests, damage-tolerance tests, and flight tests. The major difference between conventional structural certification testing and that required for aerospacecraft structures are the inclusion of thermal loads and cryogenics. Combined thermal and mechanical loadings are important, and liquid hydrogen is necessary in the tests because no other cryogenic fluid can adequately simulate it.

It was agreed that ideally, for hypersonic aircraft, elevated temperature and cryogenic conditions should be added to all categories of tests. In the case of complete vehicle ground tests, however, such addition may be not practical because of excessive costs, large electrical power requirements, and limitations of instrumentation for measuring thermal and structural response. It was suggested that a compromise may be acceptable in which the "all-up" complete vehicle combined thermal and structural static and fatigue ground testing might be replaced by (1) thermal-structural testing of major full-scale components and (2) static and fatigue testing of the complete vehicle at room temperature.

Analysis plays a major role in such a certification process. Validation of analysis is an important objective of the test program. A building block approach to the test program from coupon to full-scale major components is necessary so that subsequent tests are based on a sound foundation of correlation between test and analysis and thorough understanding of structural behavior based on previous tests. Flight testing should be based on an envelope-expansion approach, and flight testing must be considered an integral part of the overall structural certification process.

An example of the major structural component breakdown which could be considered for full-scale testing is shown in figure 17. Estimated facility requirements for the fuselage-cryotank-wing test component are shown in figure 18. Facilities of this nature currently do not exist in the western world.

Facilities engineering personnel at NASA Langley Research Center conducted a preliminary study of a national test facility for transatmospheric aerospacecraft. Results are contained in reference 17. The facility accommodates testing major full-scale components of hypersonic vehicles under combined mechanical and thermal loading and with cryogenics including liquid hydrogen. It requires 400 MW of electrical power and 2.25 Mgal of cryogenics and is estimated to cost $400M.

Because analysis-test correlation is an important objective of this certification program, the tests are not of a go-no-go nature, and accurate strain and temperature data must be acquired. In November 1988 a workshop was held at NASA Ames Dryden Flight Research Facility on correlation of hot structures test data with analysis. Attendance included over 100 experts from industry, government, and universities. Papers presented at the workshop are contained in reference 18. It was concluded that high temperature instrumentation currently is inadequate to provide the accurate and detailed measurements required for structural certification. In addition, very limited experience exists in test methods for cryotank structures, hot structures and actively-cooled structures. Attention must be directed to these deficiencies prior to entering into a certification test program on major structural components

CONCLUSIONS

Structural design of future transatmospheric aerospacecraft is a very demanding task. Structures and materials technologies are currently not ready to support such an endeavor. The following challenges must be addressed:

- o Continue developments in materials technology for application to primary structure to include--
  - ... metal-matrix composites
  - ... carbon-carbon composites
  - ... titanium aluminides
  - ... XD composites
  - ... small-diameter fibers for ceramic matrix composites
  - ... hydrogen barrier and oxidation protection coatings
- o Develop reusable, flightweight cryogenic tankage
- o Demonstrate active cooling concept for intake cowl lip
- o More study is needed on factors of safety and probabilistic approach to structural design
- o High temperature instrumentation needs to be developed
- o High temperature analysis and test methods need to be improved through correlation between analysis and experiment
- o Structural certification requirements need to be refined through joint government-contractor effort
- o New facilities with added capability must be built to conduct structural certification testing

REFERENCES

1. Hearth, Donald P.; and Preyss, Albert E.: Hypersonic Technology--Approach to an Expanded Program. Astronautics and Aeronautics, December 1976, pp. 20-37.

2. Anonymous: Round Trip to Orbit: Human Spaceflight Alternatives--Special Report. U. S. Congress, Office of Technology Assessment, OTA-ISC-419, U. S. Government Printing Office, Washington, DC, August 1989.

3. Davis, John G.; and Dixon, Sidney C.: Beyond Simulation. Aerospace America, July 1988, pp. 38-42.

4. Wieting, A. R.; and Holden, M. S.: Experimental Study of Shock Wave Interference Heating on a Cylindrical Leading Edge. Paper Number AIAA 87-1511 presented at AIAA 22nd Thermophysics Conference, Honolulu, Hawaii, June 8-10, 1987.

5. Wieting, Allan R.; Dechaumphai, Pramote; Bey, Kim S.; Thornton, Earl; and Morgan, Ken: Application of Integrated Fluid-Thermal-Structural Analysis Methods. NASA TM 100625, May 1988.

6. Stone, J. E.; and Koch, L. C.: Hypersonic Airframe Structures Technology Needs and Flight Test Requirements. NASA CR 3130, July 1979.

7. Tenney, D. R.; Lisagor, W. B.; and Dixon, S. C.: Materials and Structures for Hypersonic Vehicles. NASA TM 101501, October 1988.

8. Glass, David E.; and Camarda, Charles J.: Results of Preliminary Design Studies of a Carbon-Carbon/Refractory-Metal Heat-Pipe Wing Leading Edge. NASP TM 1071, July 1989.

9. Jackson, L. Robert; Tenney, Darrel R.; Dixon, Sidney, C.; Carter, Alan L.; and Stephens, Joseph R.: Hypersonic structures and materials: a progress report. Aerospace America, October 1987, pp. 24-30.

10. Ronald, Terence M. F.: Materials Challenges for NASP. Paper Number AIAA-89-5010 presented at AIAA First National Aero-Space Plane Conference, Dayton, Ohio, July 20-21, 1989.

11. Clark, Ronald K.; Wallace, Terryl A.; Mullaly, James R.; and Wiedemann, Karl E.: Oxidation/Thermal Control Coatings for Titanium-Aluminide Intermetallic Alloys. NASA TM 4152, January 1990.

12. Anonymous: Aerospace Highlights 1987--Materials. Aerospace America, December 1987, pp 30-31.

13. Chamis, C. C.: Probabilistic Structural Analysis Methods and Risk Assessment: Program Overview. Presented at NASP Structural Criteria Workshop, Dayton, Ohio, December 6-7, 1988.

14. Glynn, Philip C.; and Moser, Thomas L.: Orbiter Structural Design and Verification. In NASA CP 2342, Space Shuttle Technology Conference, Part 1, pp. 345-356. 1985.

15. Chevalier, R.: Concorde and safety: design, testing and certification. Aeronautical Journal, June 1974, pp. 277-283.

16. Murrow, Harold N.: Results of Studies on Test Requirements for Structural Certification. Paper Number 38 presented at Fifth National Aero-Space Plane Technology Symposium, October 17 -21, 1988.

17. Rountree, Richard B., and Marushi, Charles B.: National Facility for Structural Certification of Hypersonic Vehicles. Presented at Hypersonic Structural Certification Studies Workshop #2, NASA Langley Research Center, Hampton, Virginia, March 21-22, 1989.

18. Anonymous: Workshop on Correlation of Hot Structures Test Data With Analysis. NASA CP 3065, Volumes I and II, 1990.

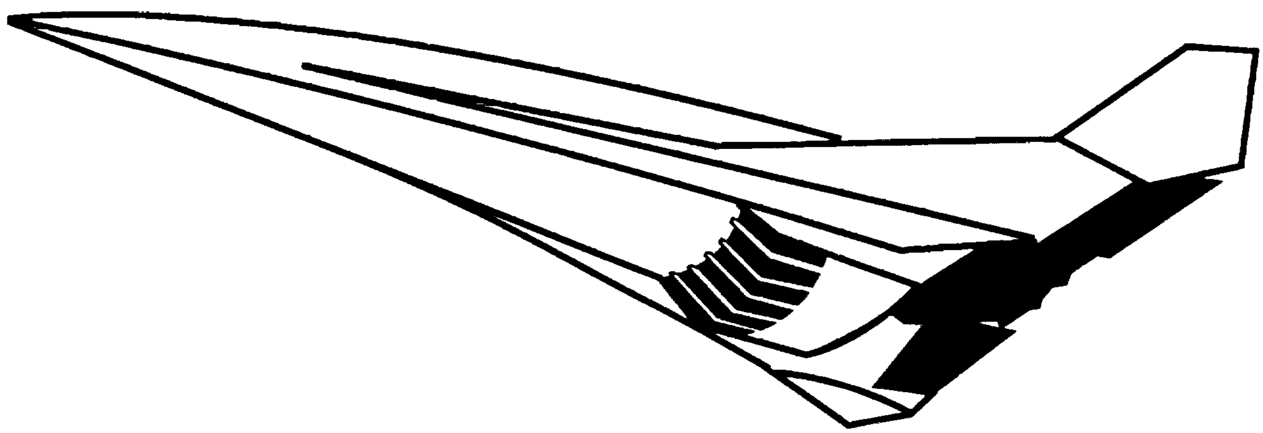
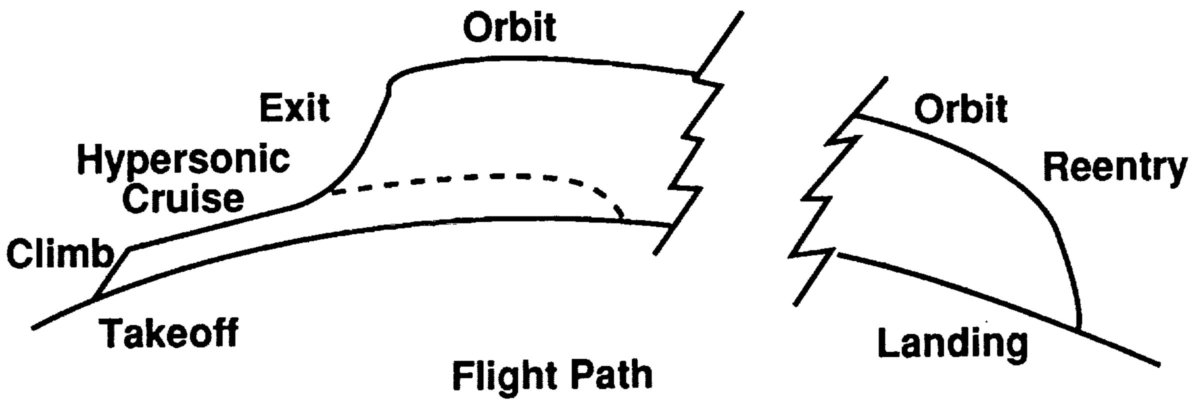


Figure 1. Transatmospheric aerospacecraft.



Major Loads Profile

Flight Phase	Loads	Flight Phase	Loads
Takeoff	Transportation Launch Thrust	Orbit	Pressure Reaction Controls
Climb	Gust Maneuver Thrust	Reentry	Thermal Maneuver Gust
Hypersonic Cruise	Thermal Aerodynamic Thrust	Landing	Touchdown Taxi
Exit	Thermal Maneuver Thrust		

Figure 2. Flight paths and major loads profile.

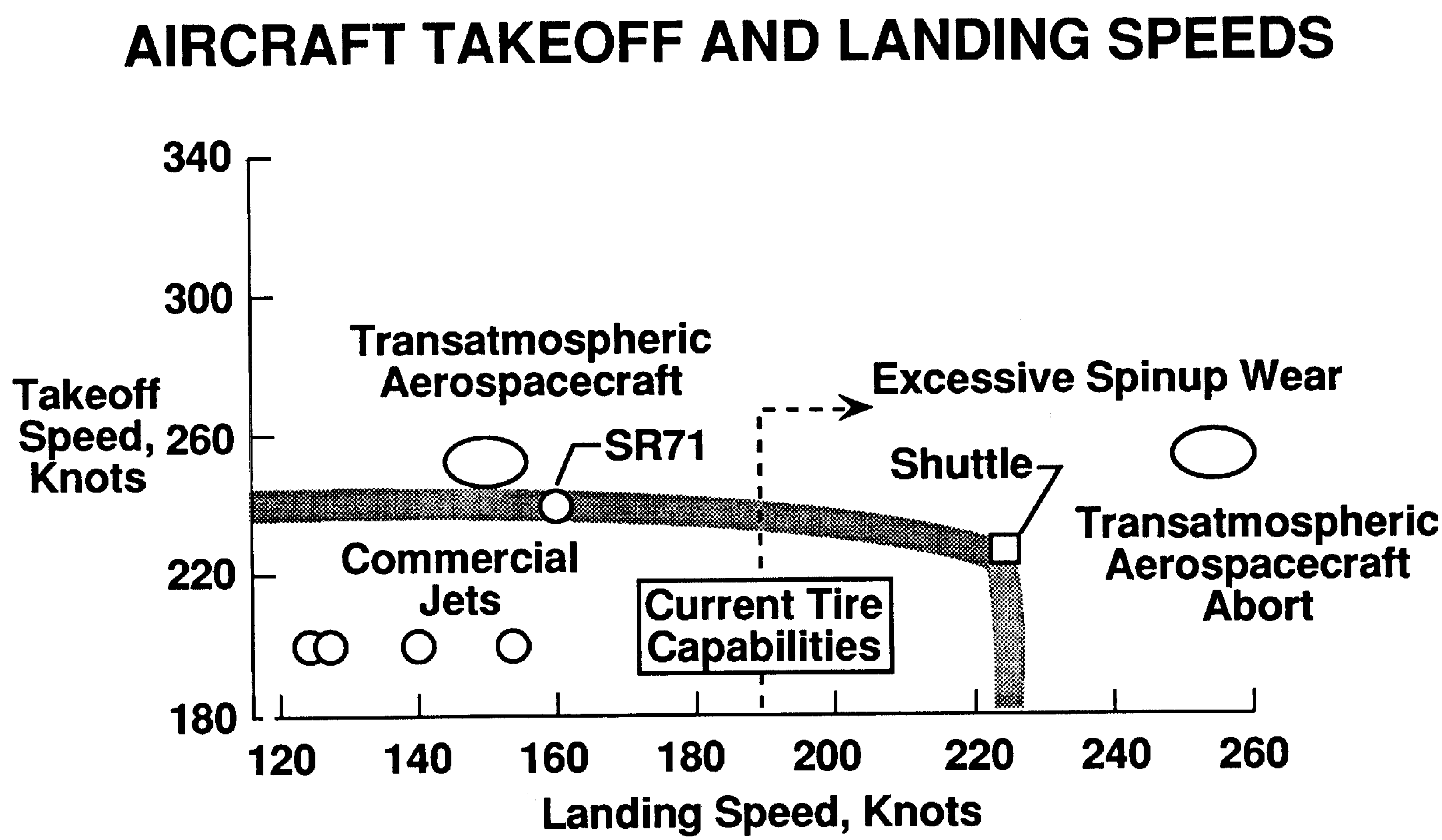


Figure 3. Vehicle takeoff and landing speeds.

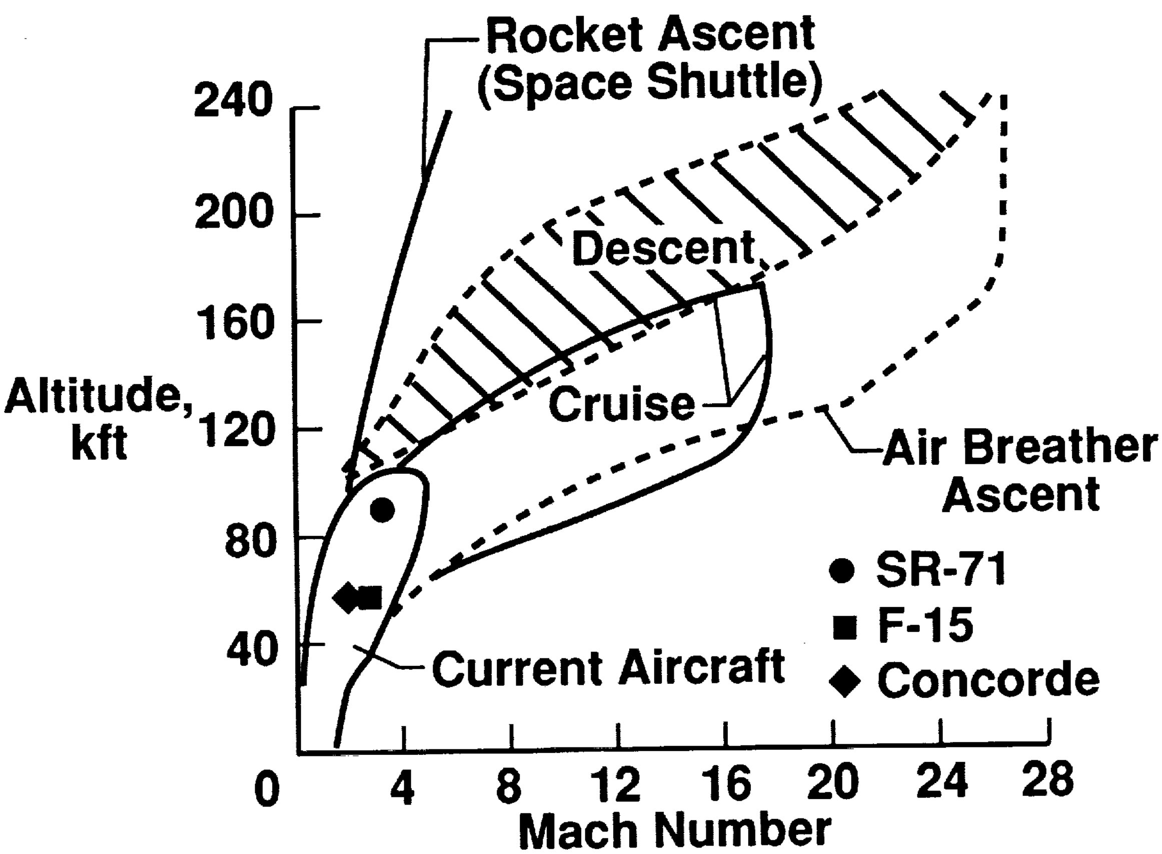


Figure 4. Flight envelopes for ascent, reentry and cruise.

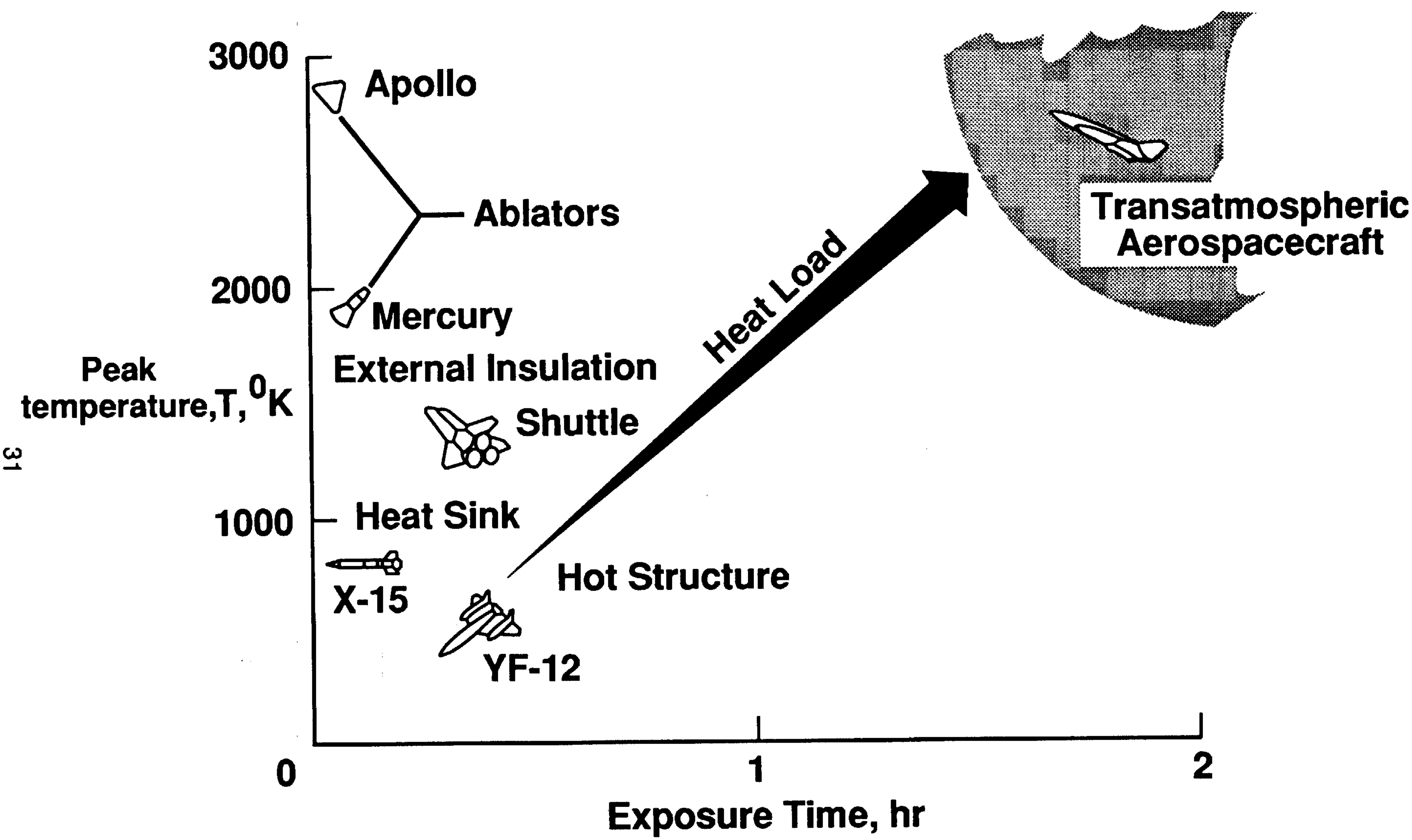
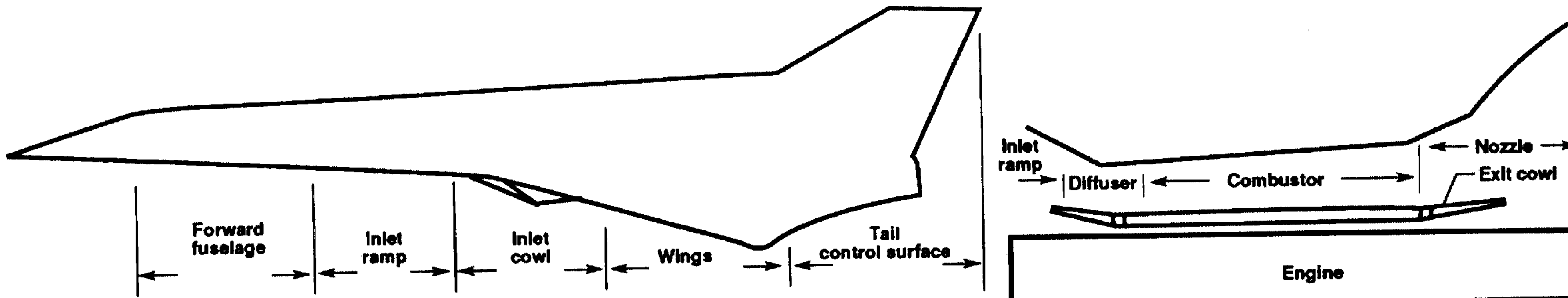


Figure 5. Thermal environments of manned hypersonic vehicles.



Requirements	Forward fuselage	Inlet Ramp	Inlet Cowl (External)	Wings	Tail Control Surface	Engine: Diffuser	Engine: Combuster	Engine: Exit Cowl (Internal)	Engine: Nozzle
Peak Heat Flux (BTU/ft^2- sec) Ascent	11 to 35	80 to 220	20 to 40	8 to 40	7 to 35	400 to 600	1100 to 1500	300 to 350	150 to 300
Descent	8 to 16	6 to 12	8 to 16	6 to 30	5 to 25	N/A	N/A	N/A	N/A
Max Aero Pressure (psf)	70 to 140	150 to 300	250 to 500	250 to 500	500 to 1400	1000 to 4000	10800 to 23000	1000 to 1400	1000 to 1400
Max Acoustic Pressure (dB)	150 to 160	157 to 165	157 to 165	160 to 176	160 to 176	160 to 176	16 to 176	160 to 176	160 to 176
Max In-plane Loads (lb/in.) • Longitudinal	200 to 600	-1500 to -2500	25 to 125	900 to 1300	-3000 to -7000	50 to 150	50 to 150	-200 to -800	-200 to -800
• Transverse	-100 to 300	500 to 1500	-25 to 25	-300 to 300	-1500 to -2500	50 to 150	50 to 150	-200 to -800	-200 to -800
Design Life • Load Cycles	1440	1440	1440	1440	1440	1440	1440	1440	1440
• Operational Life (hr)	300	300	300	300	300	300	300	300	300

Figure 6. Generic hypersonic vehicle structural design environments.

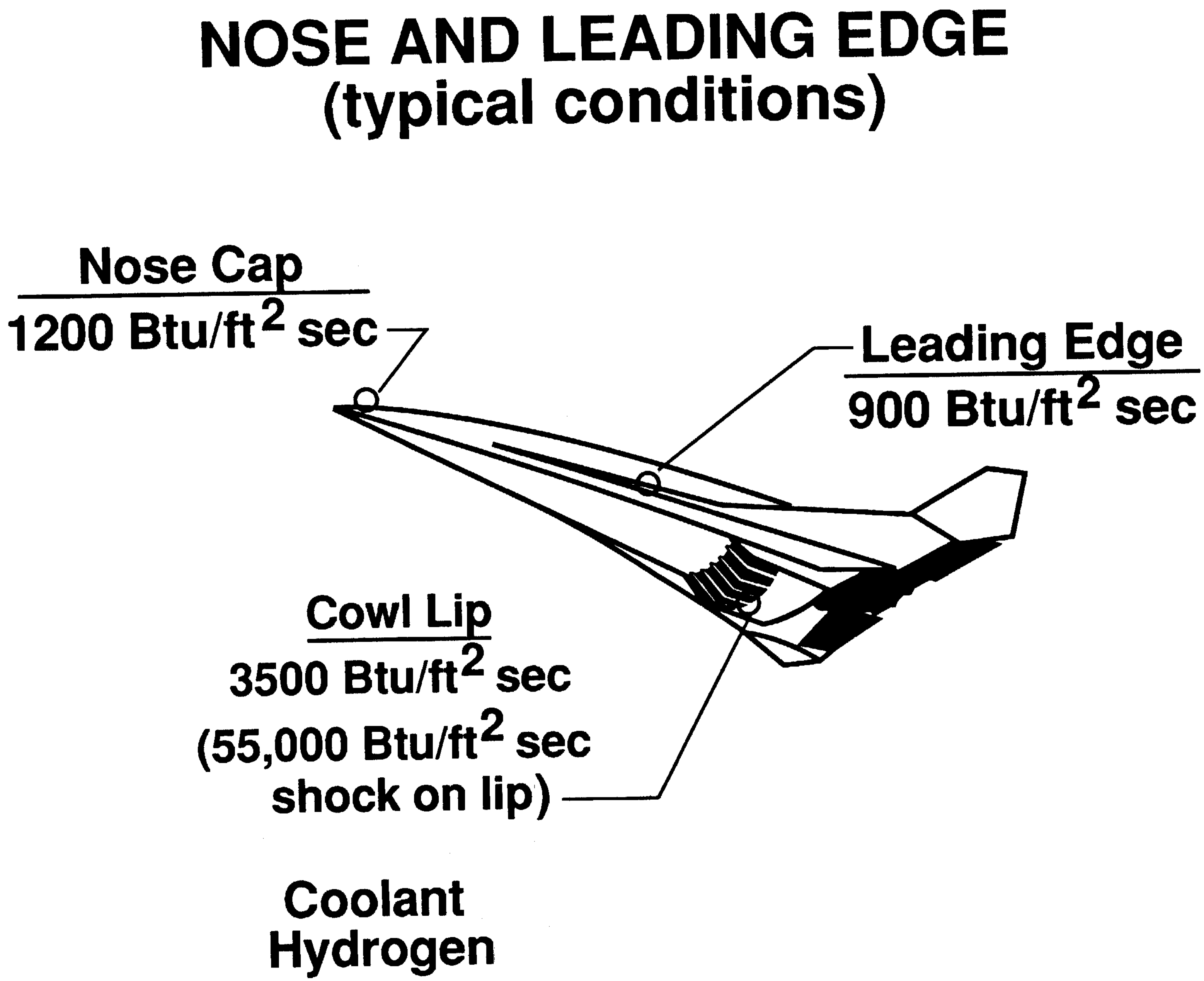


Figure 7. Nose and leading edge heat fluxes.

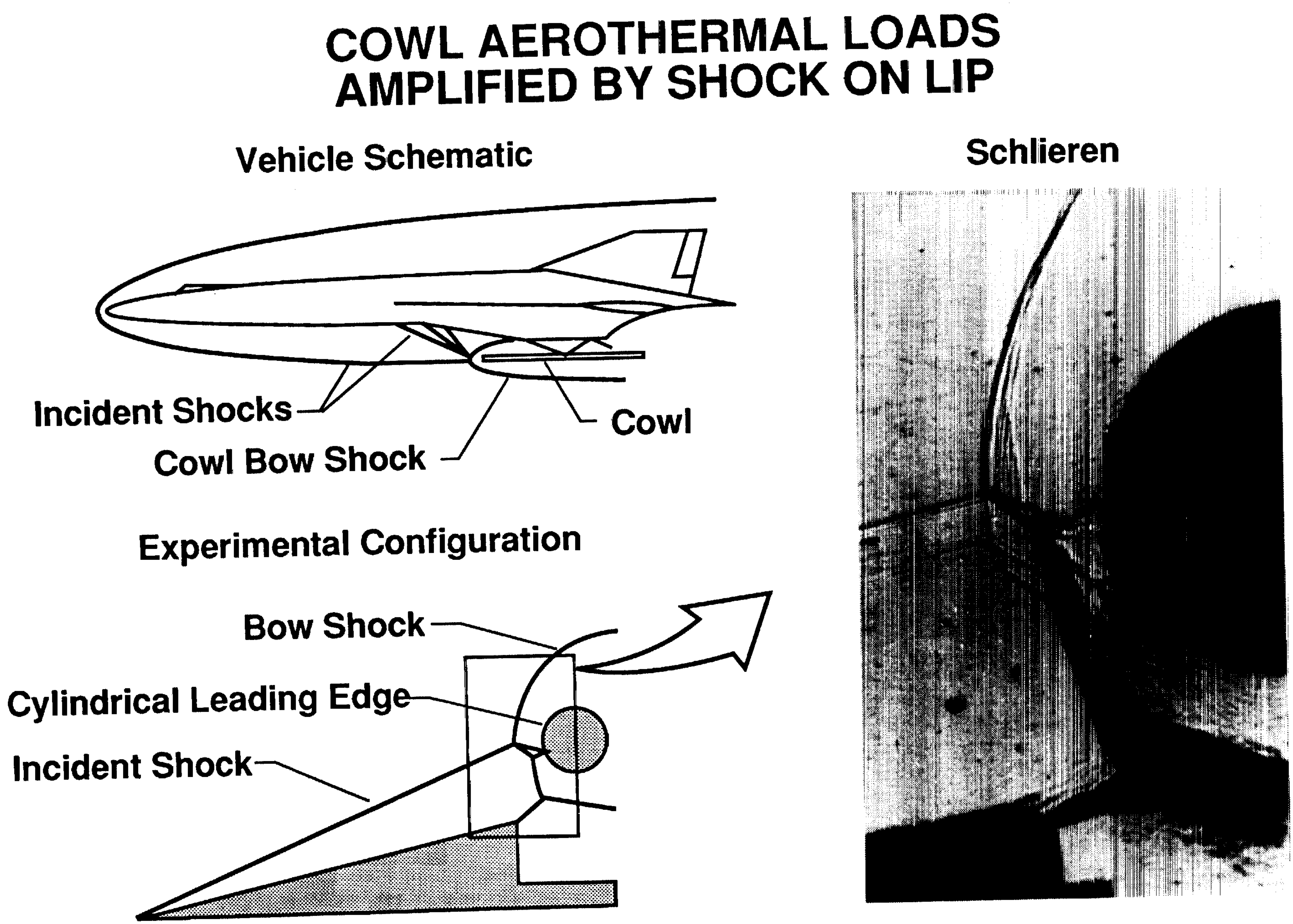


Figure 8. Shock-on-lip interference phenomenon.

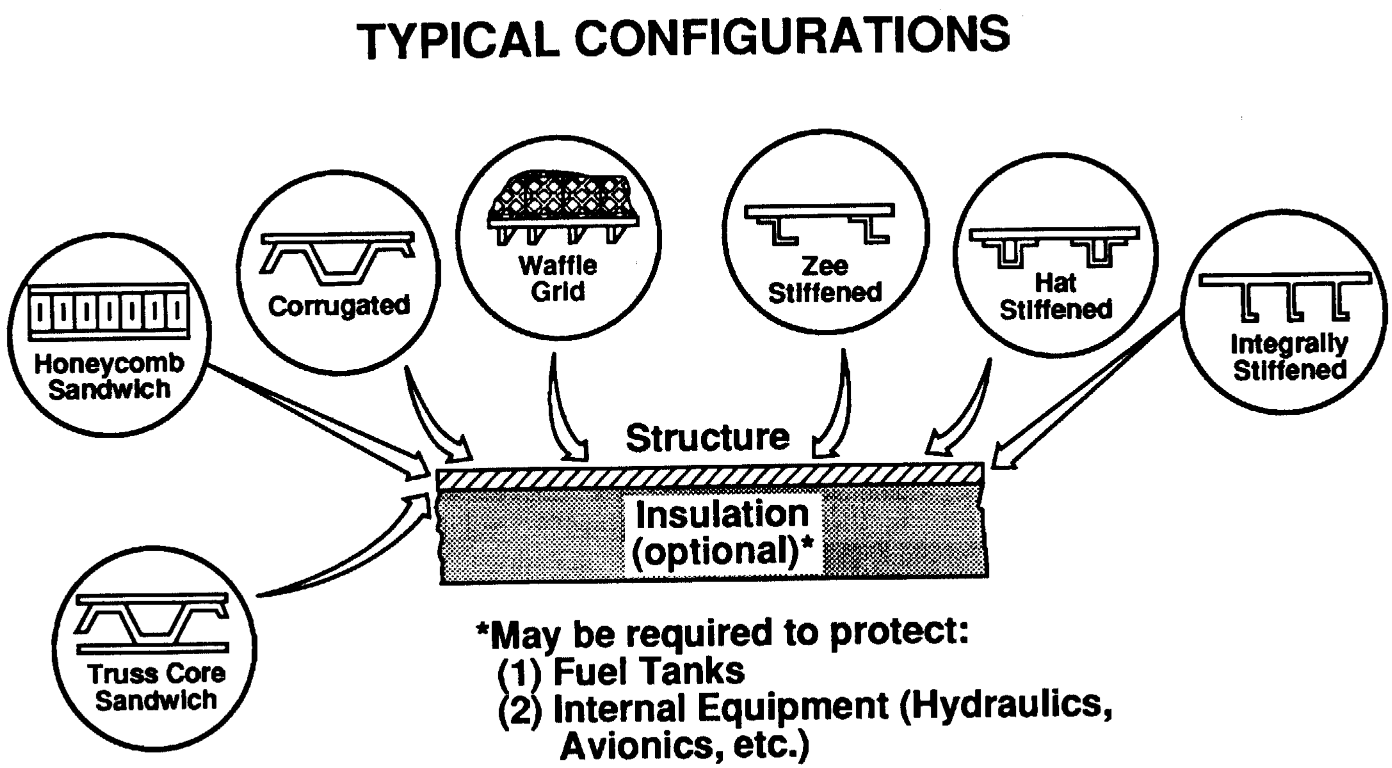


Figure 9. Hot structure.

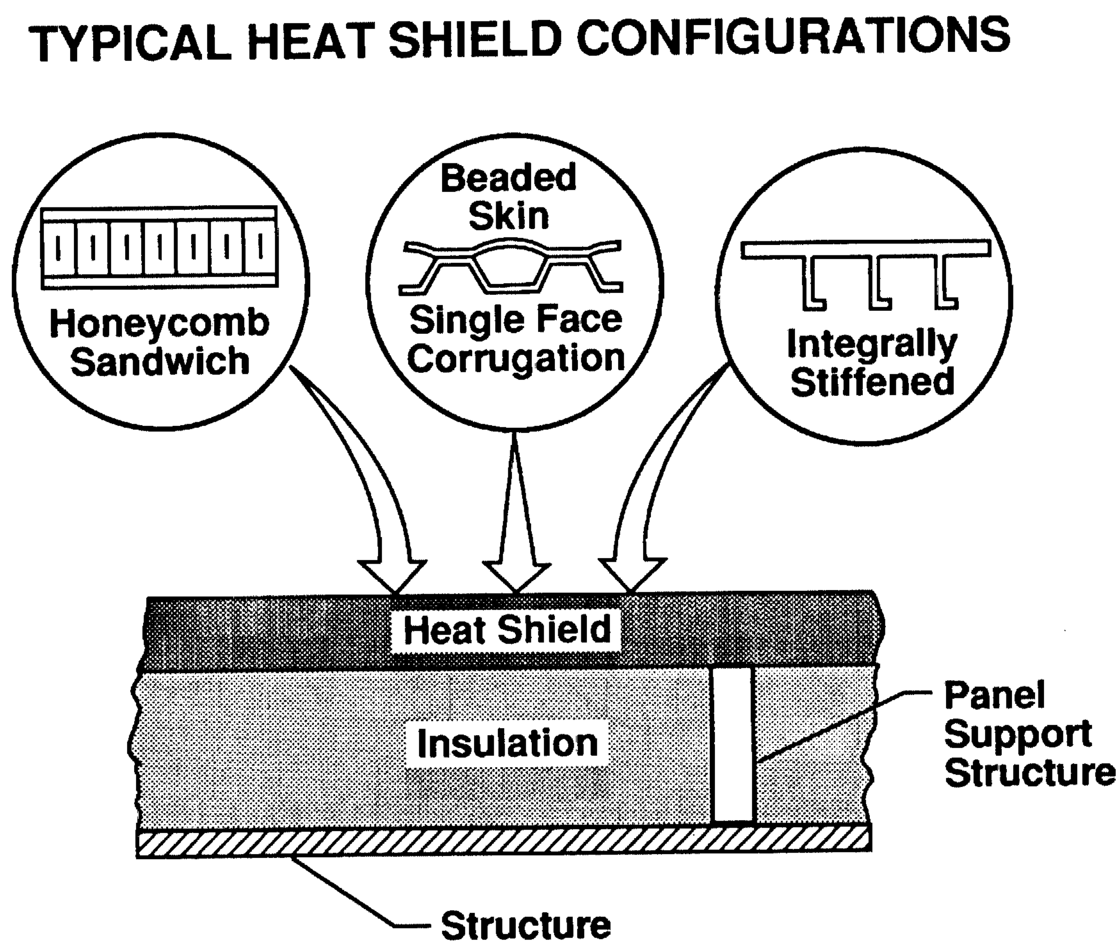


Figure 10. Radiative metallic heat shield systems.

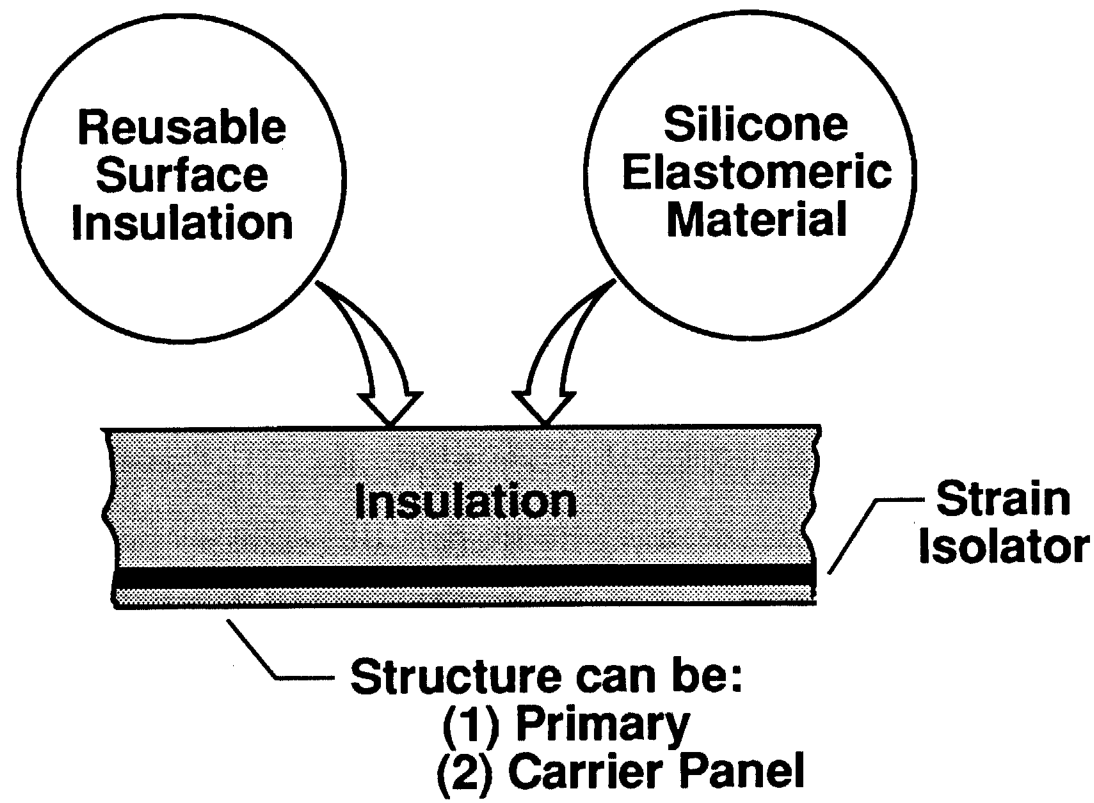


Figure 11. Externally insulated structure.

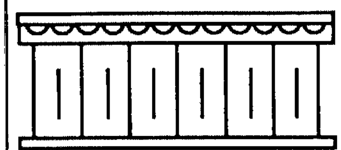
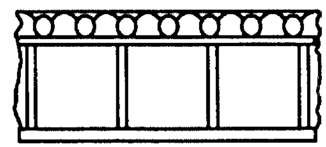
Airframe application		Inlet Ramp	Nozzle	Nozzle
Concept				
Peak heat flux-Btu/ft^{2}sec Ascent/Descent		100/7	180/2.25	1200/2.25
Acoustic-dB		160	175	180
Materials	Heat Exchanger	SiC Ti/Ti$_3$ AL	Be	Be
	Substructure	SiC Ti Skins/ Ti H/C	SiC Ti skins/ Ti Core	NA
Heat Exchanger Construction		Chem Mill Grooves	Skin and Tube	Platelet

Figure 12. Active cooled structure.

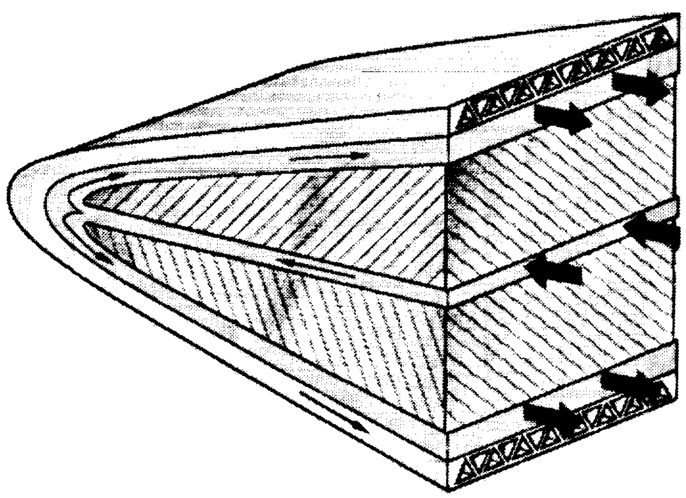


Figure 13. Active cooled leading edge.

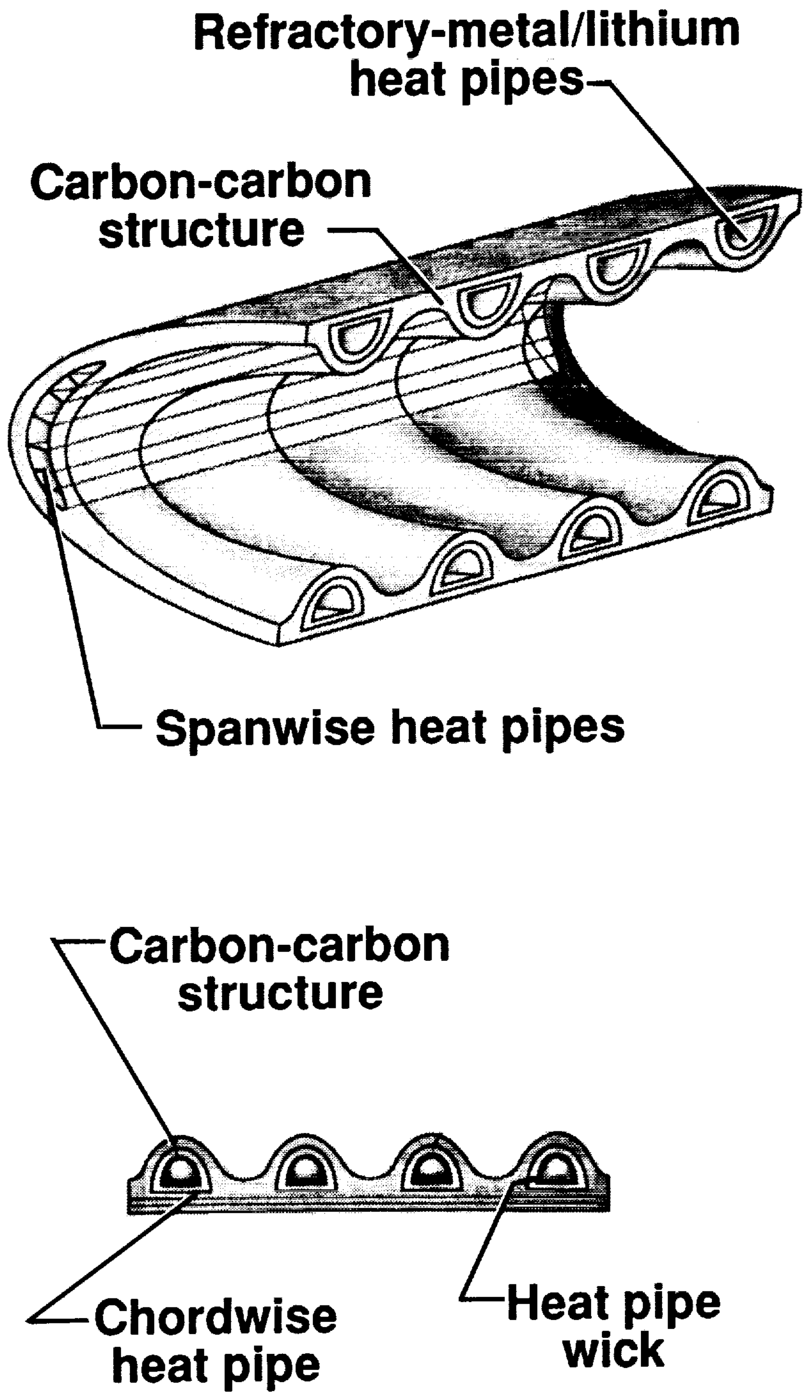


Figure 14. Phase-change-material cooled leading edge structure.

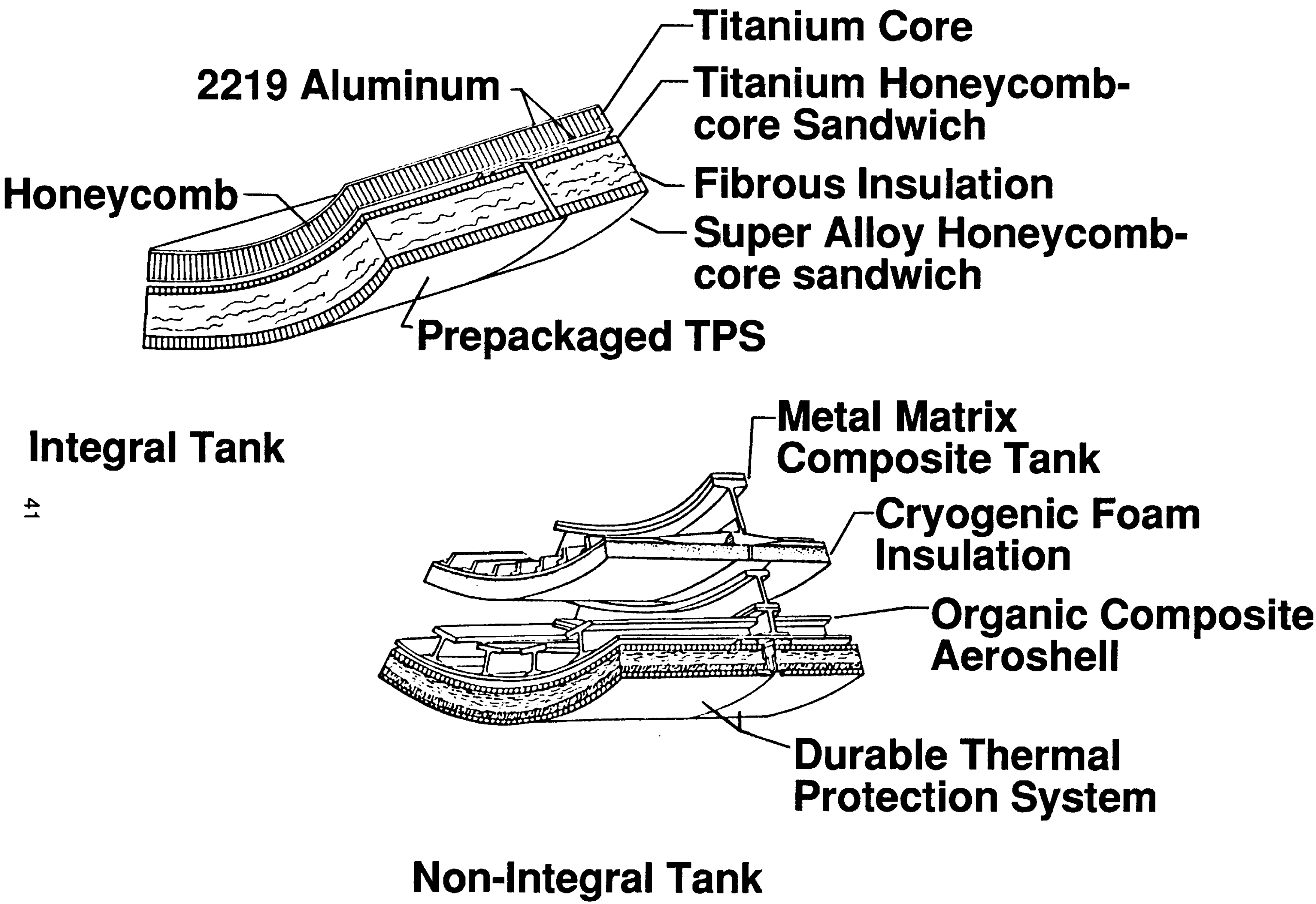


Figure 15. Structural concepts for cryogenic tanks.

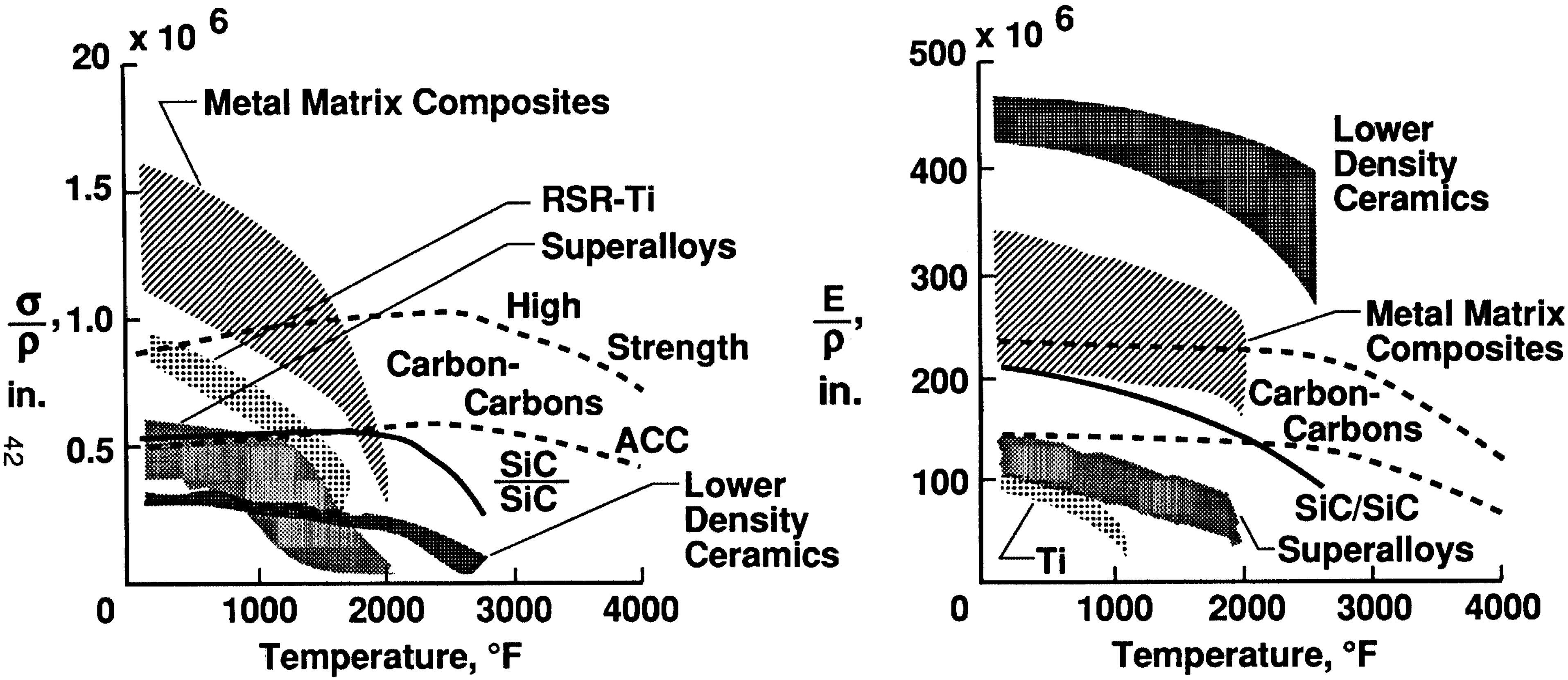


Figure 16. Specific strength and stiffness of candidate materials.

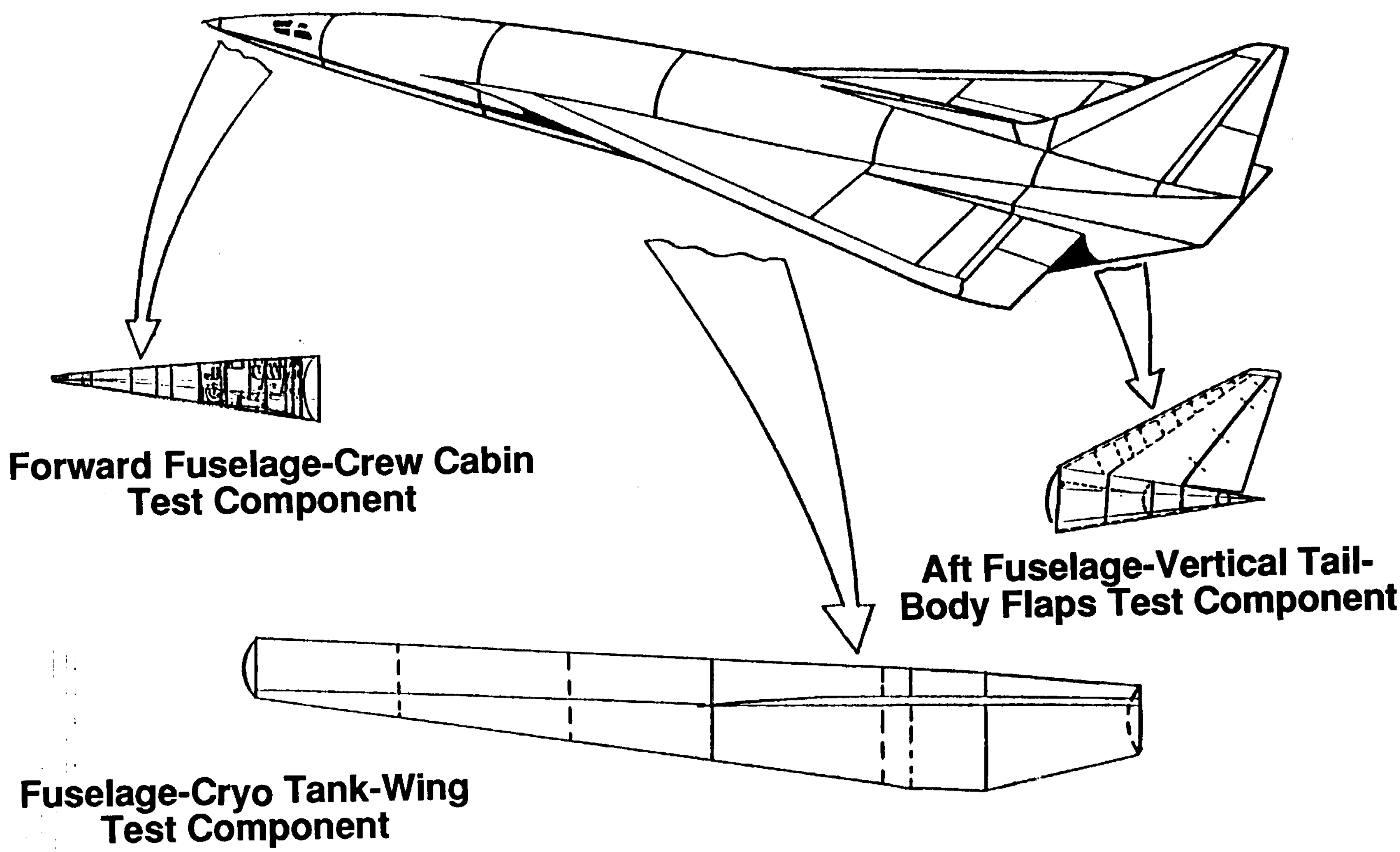
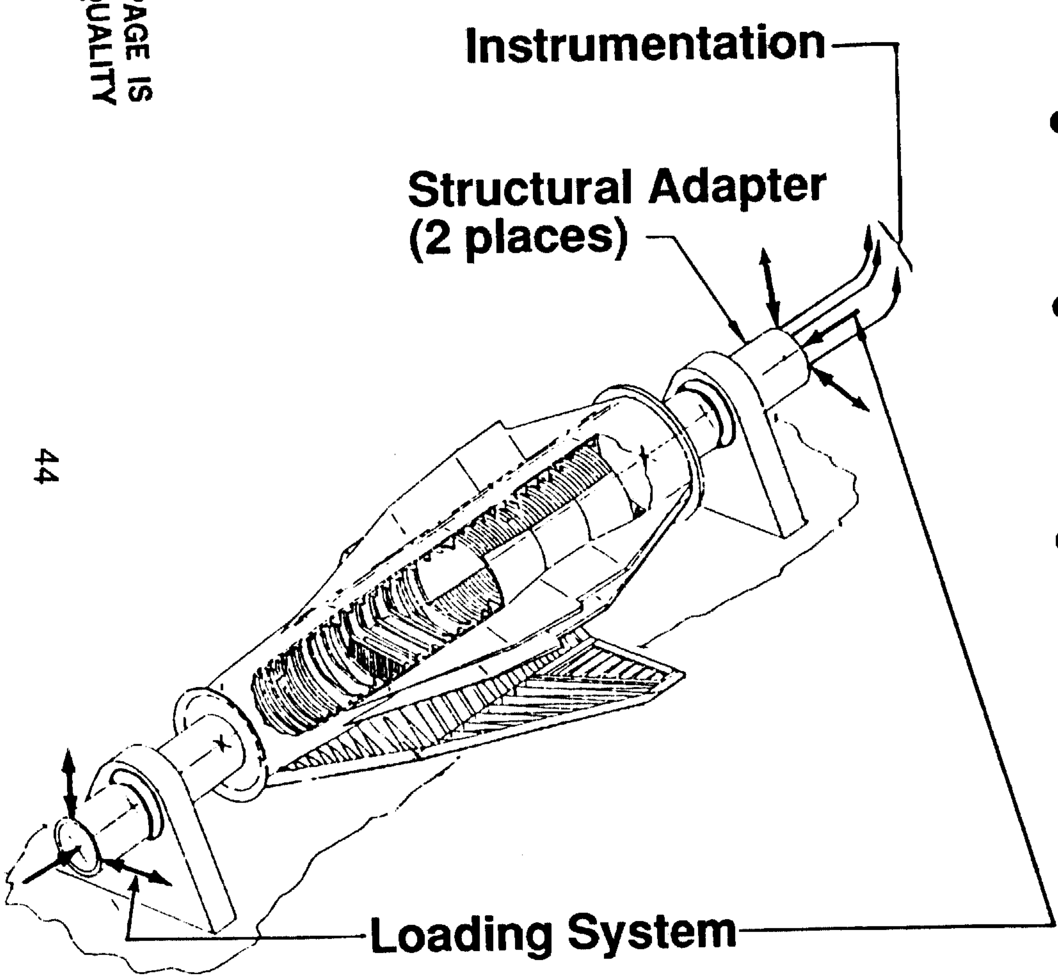


Figure 17. Major full-scale airframe structural component breakdown.



- Type of test: Full scale at elevated temperature
  - Static-to limit design
  - Fatigue-5000 missions
- Test duration:
  - Static-1 yr
  - Fatigue-3 yrs (one lifetime)
- Size~ft: (Does not include fixture)
  - Length = 100
  - Width = 65
  - Height = 30
- Facility requirements
  - Heat flux (Btu/ft^2/sec)
    Wing/body = 6 to 40
  - Estimated power (kilowatts)
    (Does not include losses)
    Wing/body = 252,200
  - Mechanical loading fixtures
  - Internal pressure and cooling

Figure 18. Facility requirements for wing/body component test.

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15. Supplementary Notes

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Harold N. Murrow and Michael F. Card: Langley Research Center, Hampton, Virginia.

16. Abstract

Major considerations in structural design of a transatmospheric aerospacecraft are discussed. The general direction of progress in structures and materials technology is indicated, and technical areas in structures and materials where further research and development is necessary are indicated. Various structural concepts under study and materials which appear to be most applicable are discussed. Structural design criteria are discussed with particular attention to the factor-of-safety approach and the probabilistic approach. The report closes with a discussion of structural certification requirements for the aerospacecraft. The kinds of analyses and tests which would be required to certify the structural integrity, safety, and durability of the aerospacecraft are discussed, and the type of test facility needed to perform structural certification tests is identified.

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